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# **IGNITION AND COMBUSTION OF BULK METALS IN A MICROGRAVITY ENVIRONMENT**

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FINAL REPORT  
NASA GRANT NO. NAG3-1685

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**University of Colorado at Boulder**

# **IGNITION AND COMBUSTION OF BULK METALS IN A MICROGRAVITY ENVIRONMENT**

## **FINAL REPORT NASA GRANT NUMBER NAG3-1685**

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### **ABSTRACT**

Results of a study of heterogeneous and homogeneous combustion of metals in reduced gravity are presented. Cylindrical titanium and magnesium samples are radiatively ignited in pure-oxygen at 1 atm. Qualitative observations, propagation rates, and burning times are extracted from high-speed cinematography. Time-resolved emission spectra of gas-phase reactions are acquired with an imaging spectrograph. Lower propagation rates of the reacting mass on titanium and of ignition waves on magnesium are obtained at reduced gravity. These rates are compared to theoretical results from fire-spread analyses with a diffusion/convection controlled reaction. The close agreement found between experimental and theoretical propagation rates indicates the strong influence of natural-convection-enhanced oxygen transport on burning rates. Lower oxygen flux and lack of condensed product removal appear to be responsible for longer burning times of magnesium gas-phase diffusion flames in reduced gravity. Spherically symmetric explosions in magnesium flames at reduced gravity (termed radiation-induced metal explosions, or RIME) may be driven by increased radiation heat transfer from accumulated condensed products to an evaporating metal core covered by a porous, flexible oxide coating. In titanium specimens, predominantly heterogeneous burning characterizes the initial steady propagation of the molten mass, while homogeneous gas-phase reactions are detected around particles ejected from the molten mixture. In magnesium specimens, band and line reversal of all the UV spectral systems of Mg and MgO are attributed to the interaction between small oxide particles and the principal gaseous emitters.

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## I. INTRODUCTION

Reactions between metals and gaseous species are important in a number of practical systems. These include: rocket propellants with metal particles added for increased thrust and suppression of combustion instability, the self-propagating high-temperature synthesis processes (SHS) to produce new high temperature materials, the combustion of metal fuels for planetary missions, and vapor-deposition processes. The combustion of metals, whether as powders or in a larger bulk form, remains an incompletely understood phenomenon due to the complex processes involved, including multi-phase thermodynamics and reaction kinetics. The first recorded measurements on the combustion of metals were performed in 1782 by Jan Ingenhousz, a Dutch engineer working in London at that time [1]. By burning fine wires of metal ignited with an electric spark, he showed that all metals known back then—with the exception of gold and silver—exhibited vigorous burning in pure oxygen.

In subsequent studies of metal combustion, considerable insight into combustion phenomena has been developed. A general framework for the combustion process is outlined in Glassman's four-point criterion for metal combustion [2]. The first general observation is that the boiling point of the metal oxide (vaporization-decomposition temperature,  $T_{vd}$ ) limits the flame temperature of the metal because the heat release from combustion is insufficient to raise the condensed oxide above its  $T_{vd}$ . The second observation is that if the  $T_{vd}$  of the metal oxide is greater than that of the boiling point of the metal ( $T_b$ ), then steady-state combustion takes place in the vapor phase (homogeneous combustion); if the  $T_{vd}$  of the metal oxide is below the  $T_b$  of the metal, then combustion takes place by a surface reaction (heterogeneous combustion). The third criterion establishes that radiation plays an important part in the combustion of metals because of the presence of condensed reactants and products. Finally, the fourth criterion suggests that the ignition process may be controlled by quite different mechanisms than the steady burning. Although not universal, these criteria provide a useful summary of many observed metal burning phenomena.

As it has been the case with many other combustion phenomena, conducting metal combustion experiments in the absence of gravity may provide further understanding of the complex physical and chemical mechanisms involved. A microgravity environment reduces the disturbing buoyant effects that frequently obscure weaker forces such as molecular diffusion. At the same time this type of environment permits detailed, longer-duration observations in large-scale experiments which are usually inaccessible due to the rapid development of buoyancy-driven disturbances. The influence of microgravity on the burning of bulk metals has been investigated by Steinberg et al. [3] in a drop tower. All metals and alloys tested supported combustion in the absence of gravity. In general, the study found that in microgravity the upward regression rate of the melting surface of a metal rod is significantly faster than in normal gravity (1 g). From the theoretical point of view, experimentation in reduced-gravity provides a unique opportunity to test analytical combustion models that usually ignore gravity effects due to the difficulties arising from the coupling of the governing equations to obtain a closed form solution. Several models of bulk metal combustion that ignore the gravitational force in their derivations [4-6] have suggested that gravity may play an important role in heat and mass transport processes that dominate metal-oxygen reactions.

Using the low-gravity environment provided by an aircraft flying parabolic trajectories, the present investigation provides new insight into the burning behavior of bulk metals in pure oxygen

at 1 atm. Titanium (Ti) and magnesium (Mg) metals were chosen to represent the two different combustion modes observed in metals: heterogeneous, multi-phase surface combustion (as in Ti) and homogeneous, gas-phase combustion (as in Mg). Metal surface temperatures, propagation rates, burning times, and spectroscopic measurements are obtained under normal and reduced gravity. Visual evidence of all phenomena is provided by high-speed photography.

## II. EXPERIMENTAL SYSTEM

The apparatus and experimental procedures employed in this investigation have been thoroughly described previously [7, 8], hence only a brief description will be given here. A schematic of the experimental system is shown in Fig. 1. The ignition source consists of a 1000-W xenon lamp that generates a highly collimated beam ( $4^\circ$  half angle) with broadband radiation (300-1100 nm). An aspheric lens focuses the beam to provide a  $2\text{-MW/m}^2$  power density on the top surface of a 4-mm-diameter and 4-mm-high metal specimen that sits on an alumina holder. A 4.5-L, stainless steel, cylindrical combustion vessel houses the lens, metal specimen, and alumina holder. Optical access for the movie camera and spectrograph is provided through two fused-silica side windows, while a third window is used for sample replacement. Ti and Mg metal specimens (99.95% purity) are placed in an  $\text{O}_2$  environment (99.6% min.) at an absolute pressure of 1 atm. The surface temperature is measured with a 0.125-mm diameter, Type R thermocouple attached to the outer wall of the sample.

A high-speed, 16-mm movie camera provides surface and flame visualization; the images are also used for measurement of propagation rates. With a  $7.5^\circ$  shutter and speeds up to 500 frames/s, exposure times as short as  $1/20,000$  s are obtained. In addition to visible light imaging, time- and space-resolved spectral information on gas-phase reactants and products is obtained with an imaging spectrograph and a 1024-element diode array detector. Various spectral ranges are covered with two motorized gratings (300 and 2400 grooves/mm). The output signal from the detector is processed by an external controller that delivers a 15-bit dynamic range and a 150-Hz readout rate with direct memory access.

The experiment is controlled entirely by a computer, a digital/analog data acquisition board, and an interface code written in graphical programming software. The low-gravity experiments were conducted onboard the NASA-Lewis DC-9 Research Aircraft in Cleveland, Ohio, U.S.A. Up to 20 s of reduced gravity ( $\pm 0.01$  g) were available in a single parabolic maneuver. A minimum of ten tests were conducted for each metal and gravity level to ensure experimental repeatability.

## III. RESULTS AND DISCUSSION

### Heterogeneous Combustion (Titanium)

For Ti the critical temperatures ( $T_{crit}$ ) of the sample—the temperature at which the heat generated by oxidation first overcomes heat losses, leading to ignition—occurs at a point on the top rim of the sample at around 1750 K. Afterward, a molten mass consisting of a mixture of metal and oxides starts traveling across the upper surface of the specimen. Under normal or reduced gravity conditions, steady downward propagation of a spherical mass follows in a smooth, nonexplosive fashion until reaching the alumina base. No evidence of emission from gaseous species is found from the visible images taken by the high-speed camera. The lack of any

significant vapor-phase reactions during this stage of the combustion process (further verified by spectroscopic measurements), points to the existence of a predominantly heterogeneous reaction with condensed products in the liquid and solid surfaces of the specimen.

Figure 2 shows a graph of the vertical distance traveled by the molten surface as a function of time for typical samples at 1 *g* and low *g*. The propagation velocities inferred from the slope of the fitted lines are 16.2 mm/s and 8.7 mm/s under normal and low gravity, respectively. Similar velocities were obtained for all the samples tested (with standard deviations of 0.6 mm/s and 0.3 mm/s for the 1-*g* and the low-*g* cases). Evaluating the ratio of propagation velocities at normal ( $V_n$ ) and low ( $V_l$ ) gravity gives a value of 1.86. A steady propagation behavior during this period at 1 *g* suggests that the propagation velocity has not been altered by the influence of the gravity force on the molten mass—also confirmed by the spherical shape of the reacting mass in the high speed photographs. Furthermore, a calculation of the Bond number ( $Bo$  = gravitational force/surface tension force) under these conditions results in values below 0.1. Acceleration can occur by lateral dripping when the gravitational force overcomes the surface tension force holding the molten mass together ( $Bo > 1$ ).

Following a theoretical approach similar to the one used for gaseous flame propagation, several studies [5, 6] have obtained an expression of the form  $V \sim (w)^{1/2}$  to calculate the propagation velocity  $V$  along metal cylinders undergoing heterogeneous surface burning with a rate of reaction  $w$ . Considering the diffusion and convection of  $O_2$  to the sample as the rate-limiting step, the reaction rate becomes proportional to  $w \sim (Gr)^{1/4}$ , where  $Gr$  is the Grashof number. The propagation velocity then depends on  $Gr$  as  $V \sim (Gr)^{1/8}$ , so that  $V \sim (g)^{1/8}$ . Evaluating  $V_n/V_l$  for the normal (1 *g*) and low gravity (0.01 *g*) cases, a theoretical ratio of 1.78 is obtained. The close agreement between experimental (1.86) and theoretical (1.78) ratios of propagation velocities indicates the importance of the influence of natural-convection-enhanced oxygen transport on combustion rates.

Upon reaching the end of steady-state propagation, the spherical molten mass is destroyed by the liquid-solid interfacial force as it touches the alumina holder. Once in the alumina base, Ti exhibits a more vigorous reaction with random outward expelling of small particles (around 150  $\mu m$  in diameter) that are expelled apparently as a result of the bursting of vapor bubbles formed inside the molten surface. These particles later undergo what appears as homogeneous gas-phase reactions and multiple fragmentation. Scanning electron microscope and electron microprobe analyses of the leftover particles reveal a hollow sphere composed of the higher oxide,  $TiO_2$ .

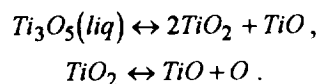
The particle expulsion stage at reduced gravity is also of longer duration than at 1 *g*. The observed differences between the normal and reduced gravity cases are due in part to the longer combustion times in low gravity. Longer residence times and the lack of convective cooling of the sample encourage higher temperatures which in turn enhance localized boiling inside the liquid blob increasing the number of particles ejected during the expulsion stage.

The longer duration of the steady-propagation and particle-expulsion stages at low gravity (almost twice as long as in normal *g*), in combination with fast spectral acquisition (one complete spectrum every 7 ms), provides an excellent opportunity to study the combustion behavior of bulk Ti specimens. Time-resolved spectroscopic measurements of the radiation emitted from the burning Ti specimen, constitute an invaluable tool for providing clues on the possible combustion mechanisms present during the different stages of the burning process. For a comparative analysis, emission spectra taken during two different times and at two different locations is presented in Figs. 3 and 4.

Figure 3 shows the radiation emitted from the volume above the reacting mass during the initial phase of the steady-propagation stage, immediately after ignition. Fig. 4 shows the emission spectra from an individual flying particle ejected from the molten mass during the particle-expulsion stage. In both cases, a broad spectrum is presented first (top figures), followed by a detailed close-up of the most relevant section (bottom figures). Some of the unidentified lines and bandheads may be the result of emission from complex polyatomic oxides and from some atomic impurities present in the metal sample.

Based on the visible images from the high-speed photographs and on the above spectroscopic results, some observations can be made of the possible physical and chemical mechanisms present during the various combustion stages. As seen in Fig. 3, a series of weak signals from Ti and TiO—along with a strong emission signal from the ubiquitous  $3^2P^0_{1/2,3/2} - 3^2S_{1/2}$  doublet of atomic sodium (Na) present as impurity—is detected during the steady propagation stage. From the low relative intensity of the measured spectra (as compared to later burning stages) and from the lack of visible evidence of gas-phase emission from the high-speed photographs, it appears that the origin of the Ti and TiO lines may come from the small concentration of Ti atoms (from its equilibrium vapor pressure at the specimen temperature) above the liquid surface and the formation of TiO from the Ti-O<sub>2</sub> reaction. The small amount of gaseous species detected (as inferred from the weak spectroscopic signals) may be the result of a reaction temperature which is below the boiling temperature of Ti ( $T_b = 3631$  K [9]) and below the vaporization-decomposition temperature,  $T_{vd}$ , of TiO, the oxide of Ti with the lowest  $T_{vd}$  (around 2970 K [10]). This low combustion temperature—attributed to the heat loss by conduction to the unburned rod and the latent heat required for the melting of Ti—explains the existence of a predominantly heterogeneous reaction with condensed oxide products in the liquid and solid surfaces of the specimen during the propagation stage.

In contrast with the low-energy radiation detected from the molten mass, the radiation emitted from the ejected particle (as seen in Fig. 4) is mostly concentrated in the high-energy part of the spectrum. The emission comes primarily from multiple Ti lines and from the  $\alpha$  (blue-green) spectral system of TiO; smaller contributions come also from the  $\beta$  (orange) and  $\gamma'$  (orange-red) systems of TiO. This radiation explains the mostly blue-green coloration seen around the flying particle. An emission spectrum shifted towards the high-energy transitions of the visible and UV spectral ranges, suggests that the ejected particle is at a higher temperature than the value estimated for the molten mass. A higher temperature is to be expected from the negligible heat losses experienced by a small-size particle completely surrounded with oxidizer gas. The abundance and intensity of emission lines from atomic Ti may further point to a temperature above the  $T_b$  of Ti. According to the first hypothesis of the Glassman criteria, in general, the combustion temperature is limited to the vaporization-decomposition temperature of the metal oxide. A combustion temperature above the boiling point of Ti would require the existence of an oxide with a  $T_{vd}$  higher than the  $T_b$  of Ti. The oxide Ti<sub>3</sub>O<sub>5</sub>, with an approximate  $T_{vd}$  of 4000 K [11], may be a possible candidate under these circumstances. In fact, the following equilibria have been suggested for the Ti-O<sub>2</sub> system at high temperatures [11] (where all products are gaseous except when noted):



Under this scenario, the highly luminous halo around the particle, would correspond to a homogeneous reaction zone where gaseous Ti (and possibly some intermediate oxides) reacts with gaseous oxygen producing  $\text{Ti}_3\text{O}_5$  under the above equilibrium conditions. The presence of TiO in both equilibrium reactions, may also explain the strong bandheads of TiO observed in the spectra shown in Fig. 4.

Due to the uncertainty on the values of  $T_{vd}$  of the various oxides, and the complex and largely unknown formation of multiple oxides during combustion, caution must be exercised when estimating the burning phase and combustion temperature of a specific metal. Nevertheless, according to the arguments given above, the existence of various combustion mechanisms (heterogeneous surface burning and homogeneous gas-phase reaction) for the same metal is thermodynamically possible and in agreement with the Glassman criteria. For a metal like Ti where the  $T_{vd}$  of one of its oxides is higher than the  $T_b$  of the metal by only a few hundred degrees, the combustion mode may switch from a gas-phase reaction to a heterogeneous surface burning (with lower- $T_{vd}$  oxide products) in a non-adiabatic situation.

### Homogeneous Combustion (Magnesium)

In the case of Mg, a critical temperature of 1050 K is obtained. Following the first flash generated by the Mg- $\text{O}_2$  vapor-phase homogeneous reaction, an ignition wave runs through the sample driven by the difference between the flame temperature (near 3430 K, the vaporization-decomposition point of MgO [11]) and the temperature of the unreacted metal, which is near the Mg boiling point (1366 K [9]). The average ignition wave speeds measured for the normal ( $V_n$ ) and low ( $V_l$ ) gravity cases are 220 mm/s and 115 mm/s, respectively. If the approximation used to compare propagating velocities in Ti rods is used to evaluate the  $V_n/V_l$  ratio of ignition wave speeds of Mg (similarly assuming a diffusion/convection controlled reaction rate), close agreement is again found between the experimental (1.91) and the theoretical (1.78) values. Owing to the irregularly shaped (a consequence of metal melting before ignition), porous, solid oxide layer surrounding the sample, no attempt was made to calculate surface regression rates. Instead, an evaluation of burning times and a qualitative discussion of important phenomena is given.

From the visible images and emission spectra measurements, the structure of the luminous flame that engulfs the sample after the passage of the ignition wave is in general agreement with the extended reaction zone model of Glassman et al. [4]. According to this model, an inner region of Mg- $\text{O}_2$  vapor-phase reaction is followed by MgO condensation; the solid MgO particles eventually pile up in the bright white flame front captured in the high-speed photographs [7]. However, a thin green emission band and a wider outer diffuse blue zone (beyond the white region) are visible in addition to the prescribed features from the model. This radiation may come from Rayleigh scattering of fine oxide particles that escape the pile-up region, from excited metal vapor created by oxide dissociation in the high-temperature front, and possibly by Mg- $\text{O}_2$  heterogeneous reactions occurring in the oxide surface in a lower temperature region [12].

The spectroscopic measurements show similar behavior in the normal and low gravity cases. The familiar UV and green systems of MgO and Mg appear as the major radiation contributors. However, an interesting feature was captured by time-resolved spectroscopic measurements during the ignition wave propagation. Figure 5 shows the time sequence of spectra for the 285.21-nm Mg spectral line, as well as the UV and green systems of Mg and MgO, from the onset of ignition to fully developed combustion in a low gravity experiment. As described in

the case of Ti, the lower propagation velocity of the ignition wave and the longer burning time experienced by Mg samples in reduced gravity (in combination with fast emission spectroscopy and high-speed photography) allows for a more detailed study of the Mg-O<sub>2</sub> flame structure and combustion mechanism.

The UV bands of MgO and the UV Mg triplet appear in emission during the early stages of the ignition process, followed by an absorption and emission equilibrium towards the end of the ignition phase. The line and band systems later exhibit reversal to absorption against an intense continuum background during fully developed combustion. In contrast, the green system of MgO and the green triplet of Mg remain in emission during the combustion stage. The 285.21-nm Mg spectral line appears in absorption at all times. It is believed that in the presence of a background radiation field nonuniformly shifted towards the short-wavelength end of the spectrum (produced by Rayleigh scattering of small oxide particles), the gas-phase emitters of the Mg and MgO UV system (distributed in the inner zone of the broad flame) will disproportionately absorb more radiation than the emitters of the green system. Consequently, the spectral signal of the UV system gradually changes from emission to absorption as the density of the radiant condensed particles increases. The high intensity of the background radiation in the UV, in combination with the exceptionally high absorption oscillator strength ( $f = 1.9$ ) of the Mg transition at 285.21 nm, is also responsible for the permanent absorption behavior of this spectral line.

During fully developed combustion, buoyancy-generated convection currents are responsible for the main differences observed in the two cases investigated. At 1 g, high convection currents enhance burning by increasing O<sub>2</sub> flux to the reaction zone and by removing oxide products that may constitute a barrier to O<sub>2</sub> diffusion. The proximity of the resulting flame front to the metal sample is an indication of fast burning rates. In comparison, at low gravity conditions, the severe reduction of convection—threefold, according to the  $(Gr)^{1/4}$  dependence—and the increased resistance to O<sub>2</sub> diffusion by combustion products diminish the oxygen transport. Thus in the reduced-gravity case a broader, outer blue zone (of stagnant oxide particles in the absence of convection currents) and an increased flame standoff distance from the metal core is detected in the high-speed photographs [7] as compared to the 1-g case. Burning times vary widely depending on the number of jets and explosions that accelerate combustion. Nevertheless, the average burning time at low gravity (3.9 s) is almost twice the average value at 1 g (2.2 s).

While in 1 g the products are swept upward by buoyancy-induced currents, condensed oxides rapidly accumulate and agglomerate in the reaction front at low gravity, producing a highly radiant flame front. Sporadic removal occurs only for large-diameter particles expelled by inertial forces and residual accelerations during the reduced-gravity trajectory ( $g$  jitter). Particle accumulation may account for the unique, unsteady, spherically symmetric explosion phenomenon observed at low gravity—which we refer to as radiation-induced metal explosion (RIME). A high particle density in the flame front generates a large heat flux to the sample. This effect raises the surface temperature and increases metal evaporation; the flexible oxide membrane that keeps Mg at temperatures below its boiling point expands as vapor pressure builds up inside the metal core. As evaporation increases, so does the flame front diameter to accommodate greater oxygen flux and maintain the stoichiometry. At the peak of the cycle, the amorphous specimen is transformed into a spherical core with twice the size of the original cylinder. Eventually, the structural integrity of the oxide layer becomes the limiting step for continued growth. At some critical diameter, the spherical shell explodes, rupturing in multiple spots and creating small jets that



relieve its internal pressure. The particles of the pile-up zone are left behind as the core shrinks to its former size. These particles are later removed by the induced flow from the jets. The full cycle lasts approximately 100 ms, and depending on the recovery time of the oxide layer (to heal all ruptures), the complete process is repeated. Up to three RIME cycles are observed in a single experiment.

#### IV. SUMMARY AND CONCLUSIONS

A study of heterogeneous and homogeneous combustion of radiatively ignited bulk metals is conducted in pure oxygen at 1 atm in a reduced-gravity environment. Lower propagation rates of the reacting mass on titanium and of ignition waves on magnesium are obtained at reduced gravity. These rates are compared to theoretical results from heat-conduction analyses with a diffusion/convection controlled reaction. The close agreement found between experimental and theoretical values indicates the importance of the influence of natural-convection-enhanced oxygen transport on combustion rates.

The lower propagation rates observed at low gravity in this study differ from the higher propagation rates in microgravity given by Steinberg et al. [3]. The disagreement arises from the different experimental configurations used. In Ref. 3, propagation rates are measured for cylindrical rods ignited at the bottom. The increase in propagation rates in microgravity is attributed to an increase in the temperature of the retained molten mass—cyclical detachment of this mass occurs during upward propagation at 1 g. The influence of the gravity force on the molten mass (whose detachment subsequently reduces heat transfer to the unreacted metal) is apparently greater than the influence of buoyancy-induced convection on oxygen transport to the reaction zone. In our investigation, the propagation velocity at normal  $g$  is measured while the surface tension force dominates over gravity (at low Bond numbers). In this manner, only the effect of gravity on  $O_2$  transport rates (the limiting reaction step) is evaluated.

Convection currents also affect the burning of Mg diffusion flames. Lower oxygen flux and increased resistance to  $O_2$  diffusion by oxide products appear to be responsible for the longer burning times observed at reduced gravity. The accumulation of condensed oxide particles in the flame front at low gravity produces a unique, unsteady, spherically symmetric explosion phenomenon in bulk Mg termed radiation-induced metal explosion (RIME). The explosions seem to be driven by increased radiation heat transfer from the flame front to an evaporating metal core covered by a porous, flexible oxide coating. The removal of stagnant products by the cyclical generation of RIMEs ensures the continuous (albeit slow) and complete burning of magnesium in the absence of convective oxygen transport in a reduced gravity environment.

The possibility of a dual combustion mode of bulk Ti—multi-phase heterogeneous reaction and gas-phase homogeneous reaction—is also explored by taking advantage of the longer combustion times available at low gravity, as well as of high-speed photography and of fast, time-resolved emission spectroscopy. Weak spectroscopic signals and no visible images of gas-phase radiation during the initial steady propagation stage points decidedly to a mostly heterogeneous surface reaction of Ti at temperatures close to 3000 K. During the particle expulsion stage, a brilliant spherical halo around the particles and prominent Ti lines and TiO bandheads in the UV and blue-green spectral ranges provide evidence of a homogeneous gas-phase reaction (close to 4000 K) occurring on the particles ejected from the molten mass. The possibility of two combustion modes in a single metal (first proposed by Brzustowski and Glassman [13]) may be

explained by the proximity of the boiling temperature of the metal,  $T_b$ , and the vaporization-decomposition temperature,  $T_{vd}$ , of its different oxides (as in the case of Ti). Depending on the heat losses from the sample, the combustion temperature may correspond to the  $T_{vd}$  of an oxide with  $T_{vd} > T_b$  (near-adiabatic combustion in the vapor phase), or alternatively to the  $T_{vd}$  of a different oxide with  $T_{vd} < T_b$  (nonadiabatic combustion with heterogeneous surface burning). Accurate measurements of combustion temperatures, detailed analysis of combustion products, and reliable high-temperature thermodynamic data of metals and their oxides are still needed to unambiguously confirm this phenomena.

In Mg samples, band and line reversal of all the UV spectral systems of Mg and MgO are detected during the transition from ignition to combustion. These anomalies are attributed to the interaction between small oxide particles exhibiting Rayleigh scattering and the gas-phase emitters of the Mg and MgO UV system.

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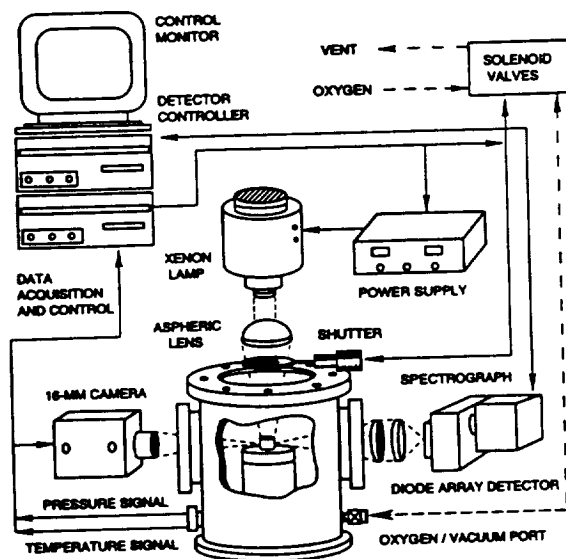


FIG. 1. Diagram of the experimental system.

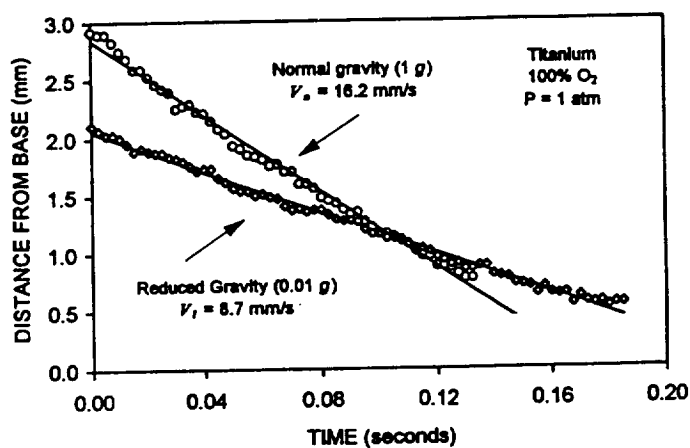


FIG. 2. Propagation of the reacting molten mass in Ti samples under normal and reduced gravity.

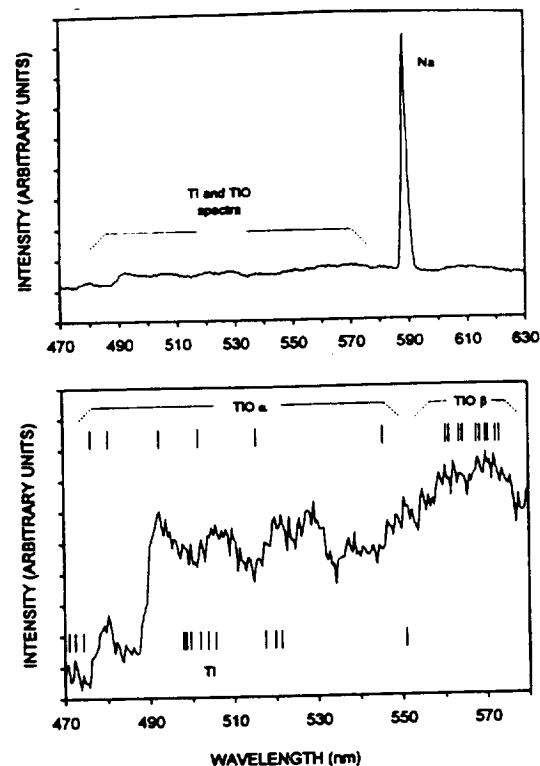


FIG. 3. Broad (top) and detailed (bottom) emission spectra obtained from a burning Ti specimen during the steady-propagation stage at reduced gravity.

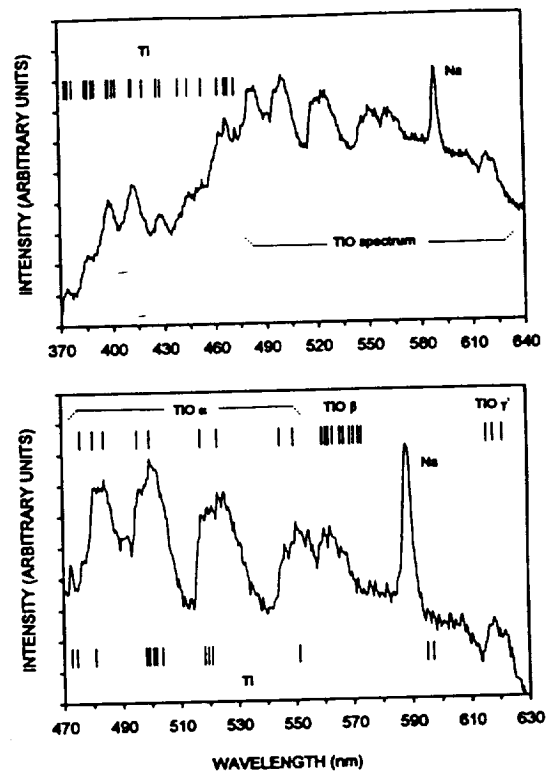


FIG. 4. Broad (top) and detailed (bottom) emission spectra of a particle ejected from the molten burning Ti specimen during the particle-expulsion stage at reduced gravity.

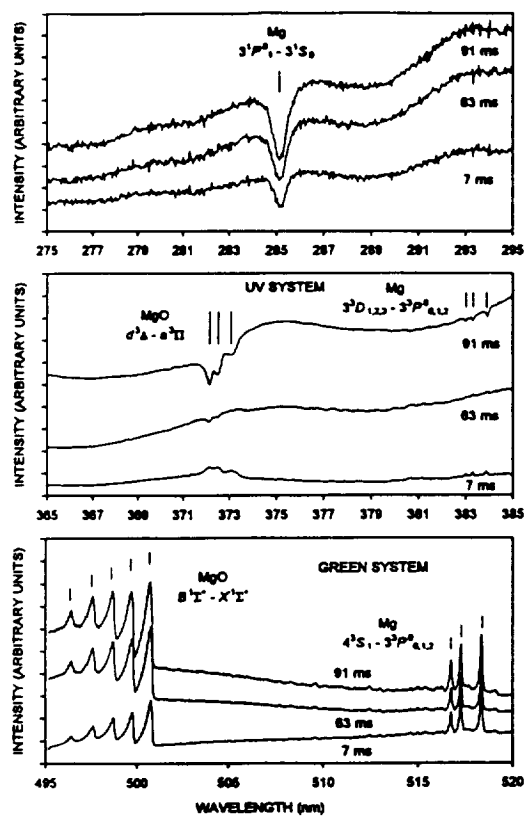


Fig. 5. Time-resolved emission spectra of the 285.21-nm Mg spectral line (top) and the Mg and MgO UV (middle) and green (bottom) systems, taken at 7, 63, and 91 ms from ignition of a bulk Mg specimen in pure  $O_2$  at 1 atm at reduced gravity.

## **VI. STUDENTS SUPPORTED UNDER THIS NASA CRANT**

1. Angel Abbud-Madrid, Ph.D., University of Colorado at Boulder, 1996
2. Wesley Rann, B.S., University of Colorado at Boulder, 1997
3. David Bunting, B.S., University of Colorado at Boulder, 1997
4. Christopher McKnight, M.S., University of Colorado at Boulder, 1998
5. Pierre Omaly, D.E.A., Universite d'Orleans, France, 1998
6. Colleen Stroud, M.S., University of Colorado at Boulder, 1998
7. Christopher Dreyer, Ph.D., University of Colorado at Boulder, in progress.

## **VII. PUBLICATIONS AND PRESENTATIONS UNDER THIS NASA GRANT**

1. A. Abbud-Madrid, *The Influence of Gravity on the Ignition and Combustion of Bulk Titanium and Magnesium*, Ph. D. Dissertation, University of Colorado at Boulder, 1996.
2. A. Abbud-Madrid, M.C. Branch and J.W. Daily, "On the Burning Behavior of Radiatively Ignited Bulk Titanium and Magnesium at Low Gravity," *AIAA Paper 96-0262*, 34th Aerospace Sciences Meeting and exhibit, AIAA, Reno, Jan. 15-18, 1996.
3. A. Abbud-Madrid, M.C. Branch, and J.W. Daily, "Ignition and Combustion of Bulk Titanium and Magnesium at Normal and Reduced Gravity," *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 1929-1936, 1996.
4. M.C. Branch and A. Abbud-Madrid, "A Study of Heterogeneous and Homogeneous Combustion of Bulk Metals in a Reduced Gravity Environment," *Bulletin des Societies Chimiques Belges*, 106, pp. 331-336, 1997.
5. M.C. Branch, A. Abbud-Madrid, and J. W. Daily, "The Effect of Gravity on the Combustion of bulk Metals," Fourth International Microgravity Combustion Workshop, NASA, pp. 23-25, 1997.
6. A. Abbud-Madrid, C. McKnight, M.C. Branch, and J.W. Daily, "Buoyancy and Pressure Effects on Bulk Metal-Oxygen Reactions," *AIAA Paper No. AIAA-98-0570*, AIAA Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1998.
7. J.W. Daily, C.B. Dreyer, A.L. Brown, A.A. Madrid, and M.C. Branch, "Laser Induced Fluorescence of MgO in a Flame," *WSS-CI Paper 98S-12*, Western States Section-Combustion Institute Spring Meeting, Berkeley, California, March 1998.
8. J.W. Daily, C.B. Dreyer, A.A. Madrid, and M.C. Branch, "Laser Induced Fluorescence Measurements of Magnesium Oxide," *WSS-CI Paper 98F-25*, Western States Section-Combustion Institute Fall Meeting, Seattle, Washington, October 1998.
9. A.A. Madrid, P. Omaly and M.C. Branch, "Experimental and Kinetic Modeling Investigation of the Structure of Magnesium-Carbon Dioxide Diffusion Flames," *WSS-CI Paper 98F-27*, Western States Section-Combustion Institute Fall Meeting, Seattle, Washington, October 1998.
10. P. Omaly, "Combustion of Magnesium in Reduced Gravity and Extraterrestrial Environments," *Diplome d'Etudes Approfondi*, University of Orleans (France), September 1998.
11. M.C. Branch, "Studies of the Combustion of Metals," presented at the ASSM Conference, University of Orleans (France), September 29, 1998.